Tunable, resonant heterodyne interferometer for neutral atomic hydrogen measurements in tokamak plasmas*

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Outline

I. Explain the physical basis for the diagnostic

II. Describe the apparatus

III. Example of measurements using pulsed plasmas

IV. Concluding remarks

Program overview

- A two wavelength interferometer has been developed to measure the n=2 state densities of H, D, or T in a plasma. This is intended for use in studying tokamak edge physics.
- One of the wavelengths is resonant with the *2p-3d* transition (ie. H_α, D_α, T_α) and is adjusted using a tunable diode laser.
- The other wavelength measures off-resonant effects, ie. index variations due to free electrons, vibrations etc.
- By varying the laser wavelength during the discharge, information on the line shape and center can also be determined.
- All quantities are determined from the measured phase shift, therefore no intensity calibration is required.
- All measurements are integrated along the laser beam line-of-sight with a transverse spatial resolution of less than 1 mm.

Spectral line interferometry

- Near an optically allowed transition in a given species, the refractive index is significantly enhanced. The enhancement depends on the:
  - absorption oscillator strength
  - line shape
  - laser wavelength or frequency
  - population density of the species in the lower state

- Analysis from Measures, *Appl. Opt.* **9**(3) (1970)

$$\Delta\phi = \frac{NDf}{\beta} P(u,\alpha)$$

$$\beta = \left(\frac{\omega_o}{c}\right)\left(\frac{2kT}{M}\right)^{1/2} \quad \text{(Doppler width)}$$

$$P(u,\alpha) = r_o c(\pi)^{1/2} \int_{-\infty}^{\infty} dy \frac{(y-u)e^{-y^2}}{(y-u)^2 + \alpha^2}$$

$$u = \frac{(\omega - \omega_o)}{\beta} \quad \text{(frequency normalized to} \beta\text{)}$$

$$\alpha = \frac{\gamma}{2\beta} \quad (\gamma \ \text{is the collisional width})$$

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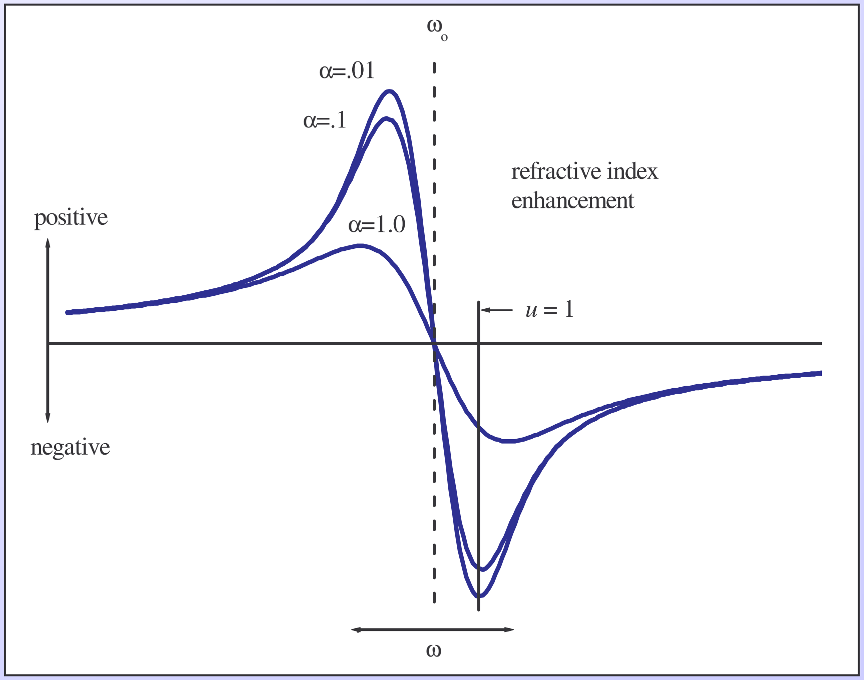

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A non-resonant laser interferometer is required to isolate the resonant effects

λ_R ⇦ free electrons + vibrations + desired species state density

λ_N ⇦ free electrons + vibrations

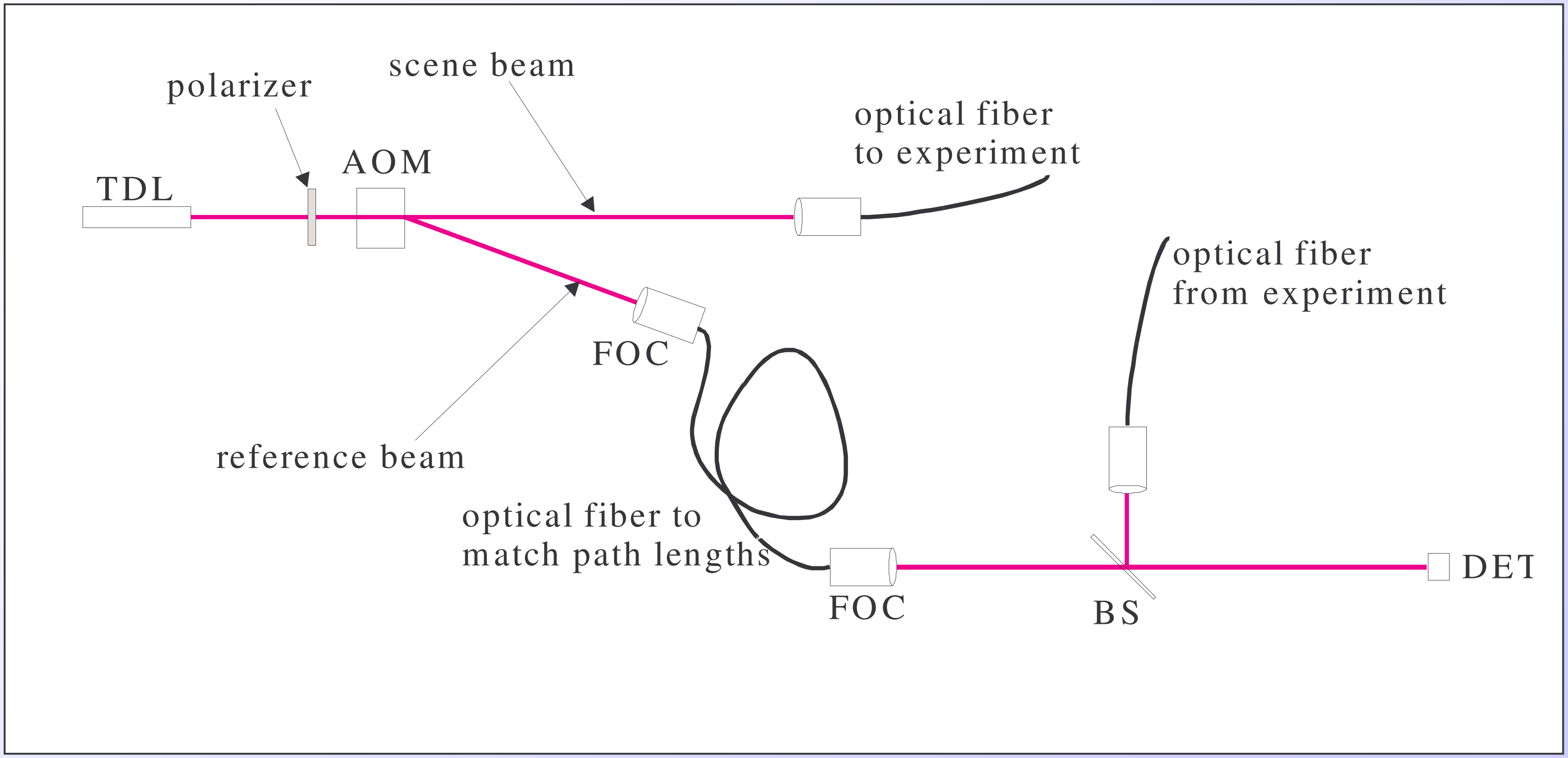
- For this to function optimally λ_R and λ_N must have common paths so environmental factors are the same for both interferometers.

Interferometer design

- λ_R from a low power (10 mW) tunable diode laser 6500-6600 Å (~10 k$)
  - can be used for H_α , D_α , T_α , or CII (6578, 6583)
- λ_N from a HeNe laser at 6320 Å
- Both interferometers use a heterodyne detection system where an AOM is used to shift the reference beams by 40 MHz.
- λ_R & λ_N are combined and fed into a single mode optical fiber.
- Fibers are used to bring the beams to and from the experimental apparatus.
- λ_R & λ_N are split and sent to individual detectors.

Apparatus schematic (I)

- All components are located in an electrically shielded room isolated from vibrations



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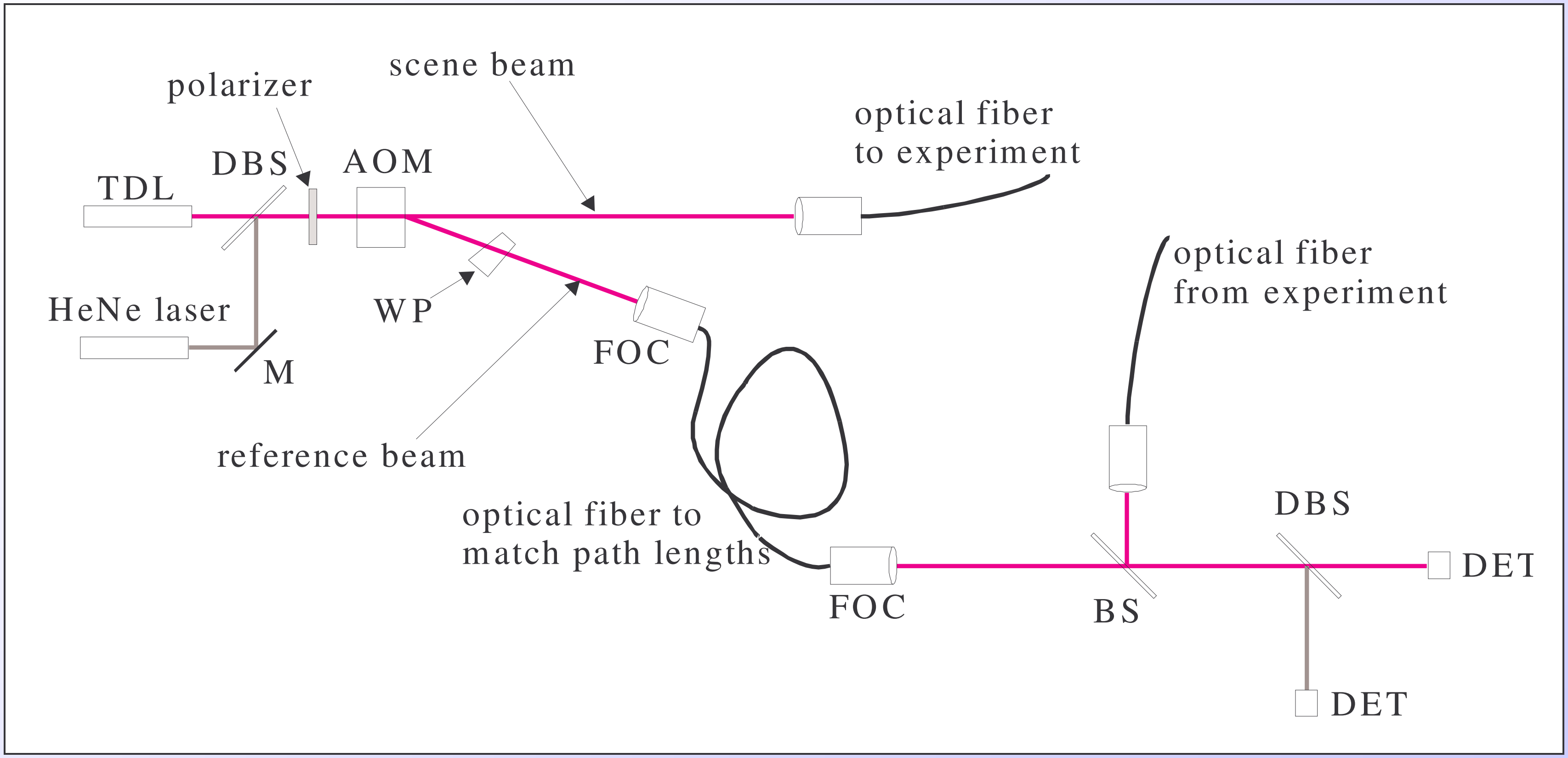
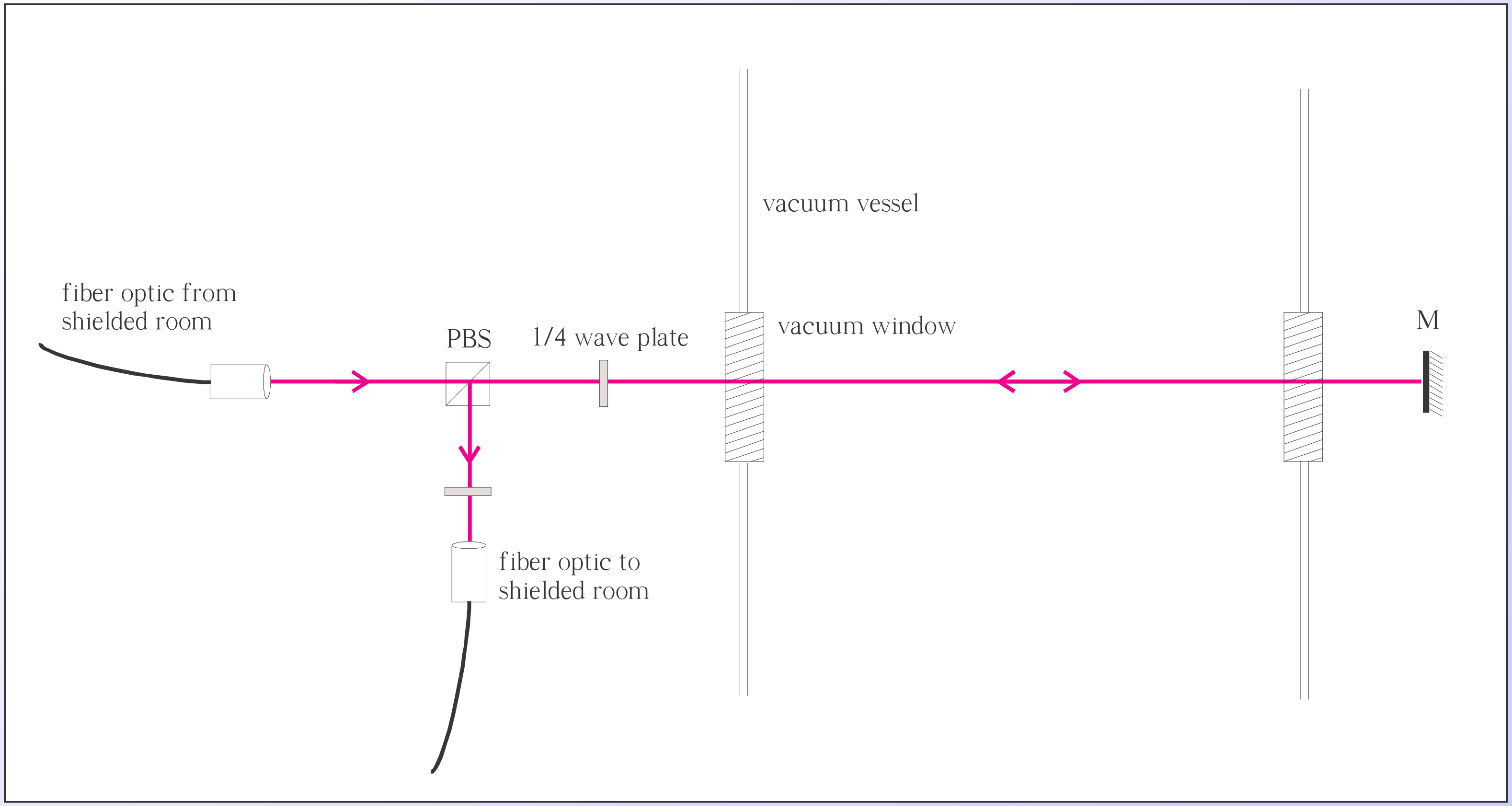


Apparatus schematic (II)

- Laboratory configuration used during the Phase I testing



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Minimum estimated sensitivities for phase detection measurements with a heterodyne interferometer.

T(eV)	n_{min}[n=2](cm^{-2})	n_{min}[n=1](cm^{-2})*
10	9.0×10^{9}	2.2×10^{12}
25	1.4×10^{10}	3.8×10^{12}
50	2.0×10^{10}	5.3×10^{12}

*Based on calculations of Johnson and Hinnon, L.C. Johnson and E. Hinnon, *J. Quant. Spectrosc. Radiat. Transfer*, **13**, 333 (1973).

Comparison with alternative techniques (H_α emission and L_α LIF)

- **State Density**
  - Resonant phase measures n=2 state density (no calibration).
  - Emission measures n=3 state density (absolutely calibrated).
  - LIF (1220 Å) measures n=1 state density .
- **Spatial resolution**
  - Resonant phase has sub-millimeter resolution in transverse direction while integrating alone the line-of-sight.
  - Emission has low spatial resolution and requires multiple sensors and complex inversion techniques to improve resolution.
  - LIF provides local information.
- **Spectral resolution**
  - Resonant phase $\geq 3\text{x}10^{-5}$ Å defined by laser linewidth.
  - LIF typically $\geq 5\text{x}10^{-3}$ Å
  - Emission typically $\geq 5\text{x}10^{-2}$ Å defined by spectrometer.
- **Temporal resolution**
  - Resonant phase: 2 ms with full spectral scan, 25 ns (40 MHz) at fixed λ.
  - LIF limited to 25 Hz laser pulses ~ 40 ms
  - Emission depends on the detector.

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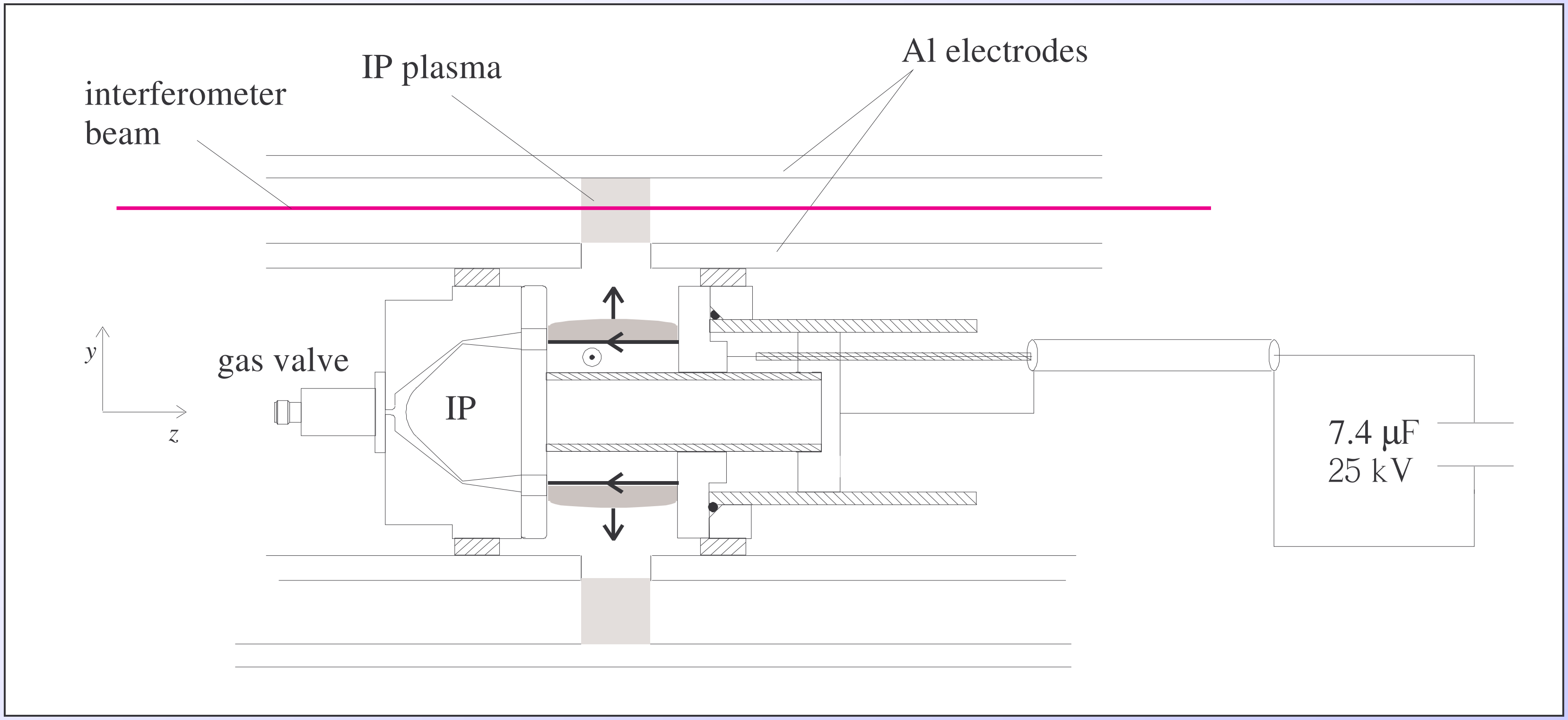
Phase I experimental test-bed

- Use the gas driven, inverse pinch (IP) plasma source (inverse z-pinch geometry).
- IP source was mounted inside a coaxial plasma opening switch.
- Plasma duration ~ 1 μs, density ~ 10^{15} cm^{-3}, T_e ~ 1 eV, 1-5 cm axial length.



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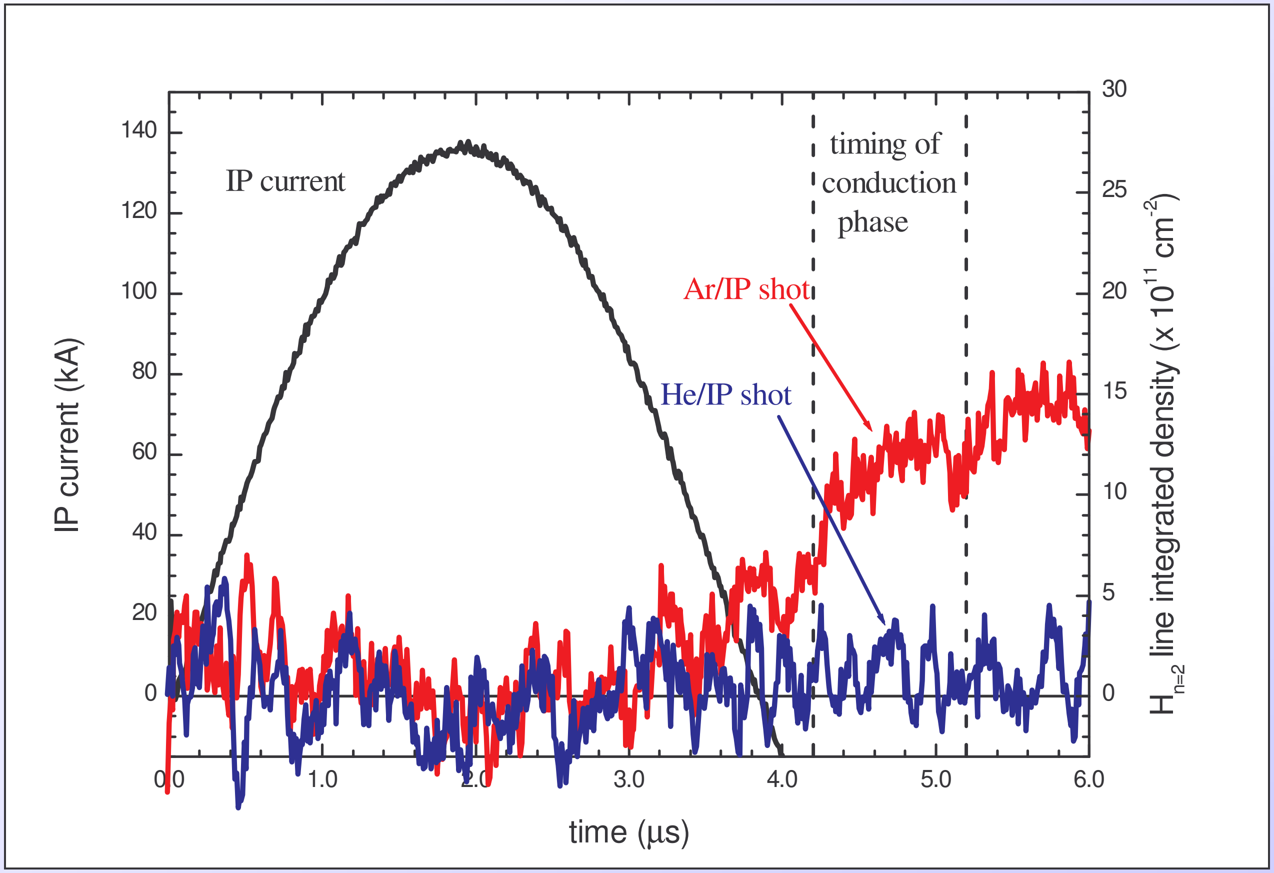
Results of the IP surface interaction

- Motivated by observation of low impurity concentrations in H/POS shots and high concentrations in Ar/POS shots.



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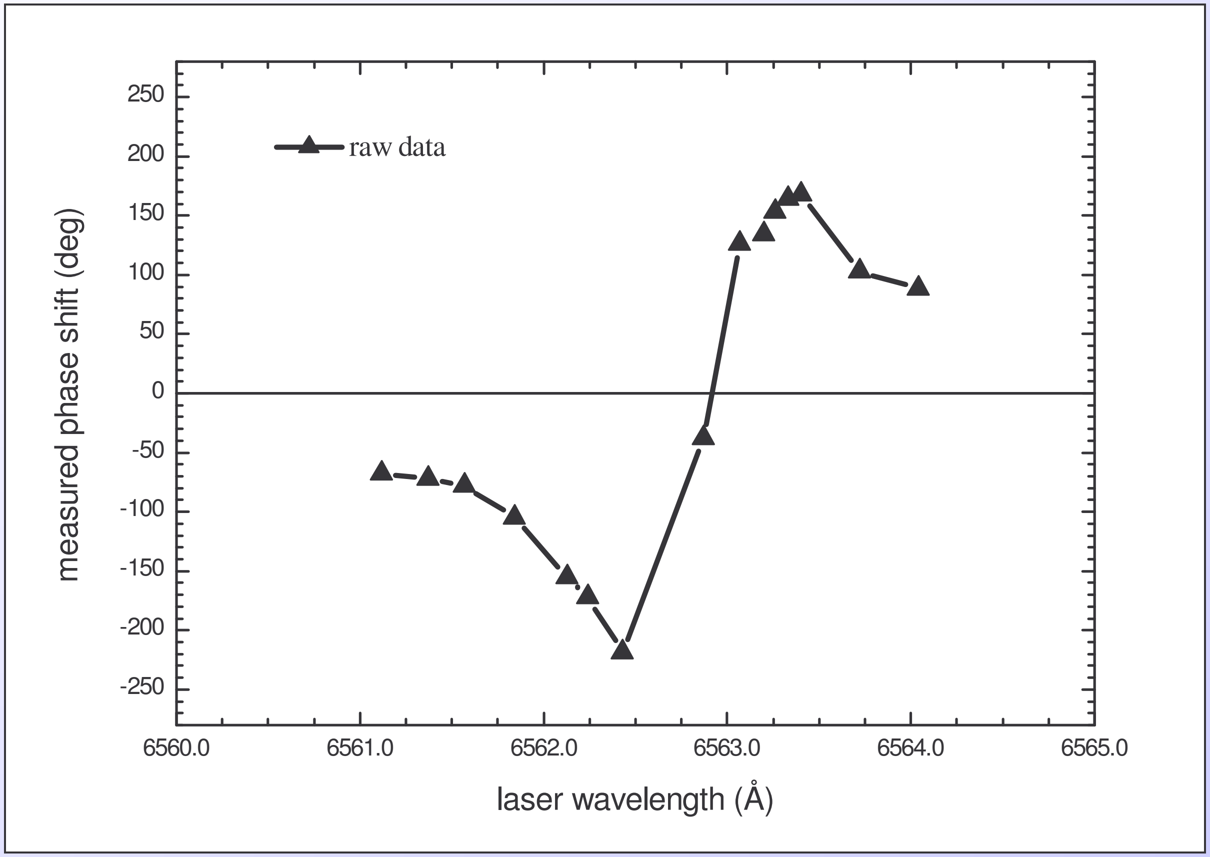
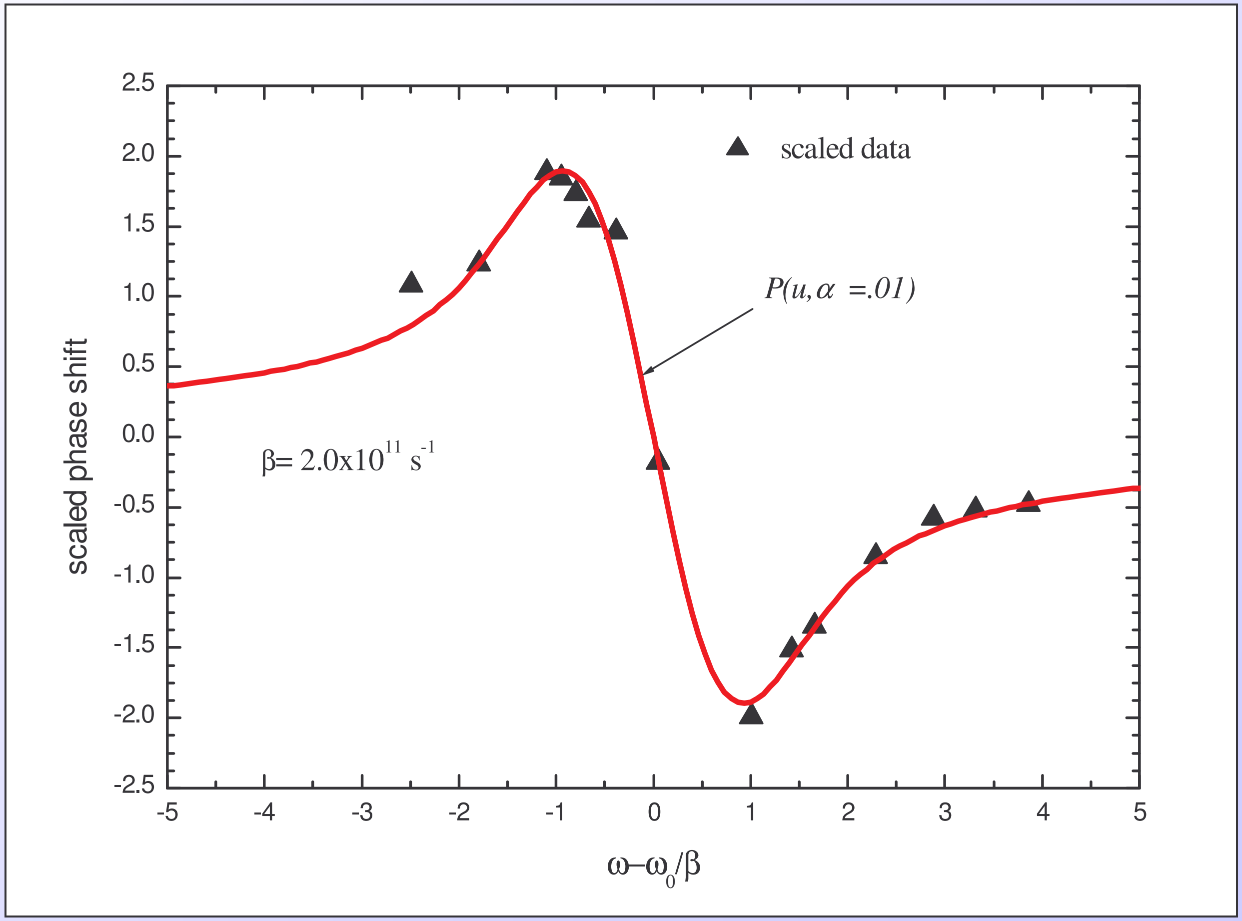
The behavior of the $P(u,\omega)$ function was verified

- The IP was used with H_2 gas in the POS configuration
- 12 shots were taken at different laser wavelengths

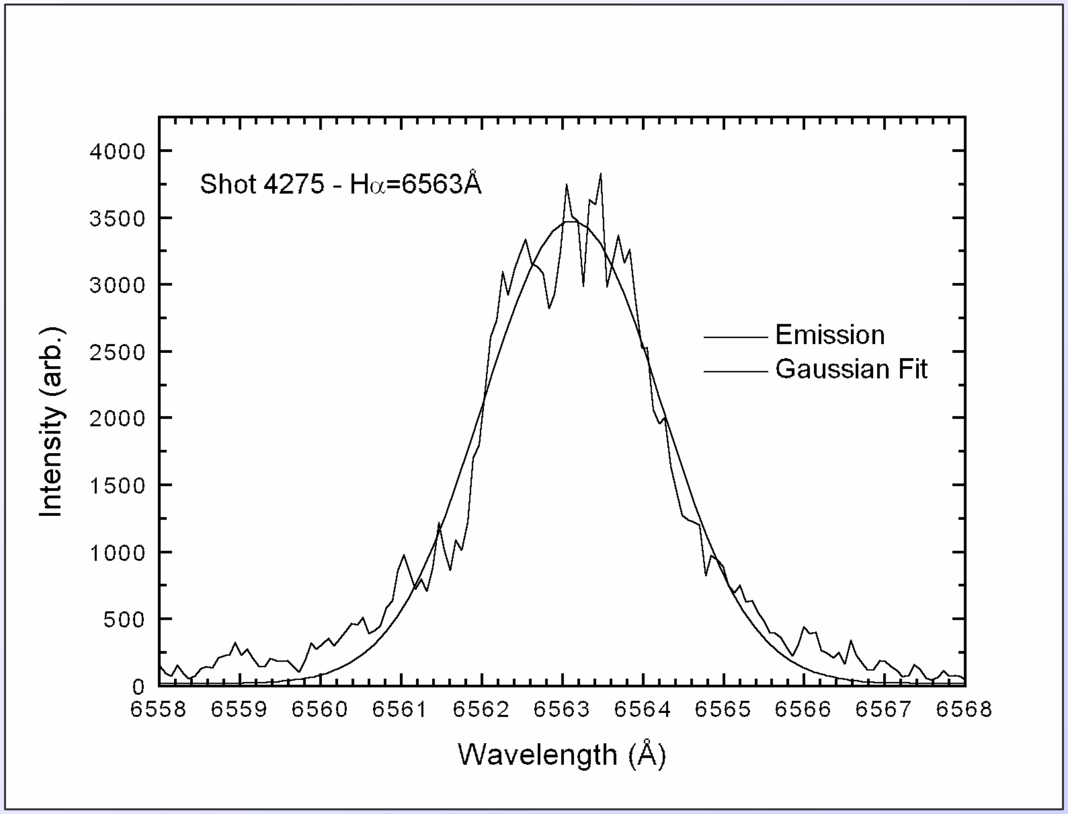


Details of the line were determined from the data

- β was determined from the peaks in the phase assuming α was small.
- wavelength was converted to $(\omega-\omega_o)/\beta$
- $P(u,\alpha)$ for $\alpha = .01$ fit the data reasonably well
- This result implies a line that is ~ 1 Å wide (T= 2.3 eV).



The deduced line profile compares well to that previously measured by emission



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Status of project

- Phase I program has been completed and Phase II proposal submitted
- The Phase II includes a cooperative arrangement with GA
- The Phase II program calls for expanding the diagnostic to a muti-chord system.

Concluding remarks

- The Phase I program has resulted in a working diagnostic.
- The diagnostic was used to measure the H (n=2) state density using a pulsed plasma device.
- The line width was also determined from the analysis and agrees with a previous emission measurement under the same conditions.